IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

APPLICATION FOR PATENT

SYSTEM FOR MEASURING POLARIMETRIC SPECTRUM AND OTHER PROPERTIES OF A SAMPLE

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BACKGROUND OF THE INVENTION

This invention relates in general to non-destructive techniques for measuring surface parameters of samples and, in particular, to a system for measuring polarimetric spectrum and other properties of a sample.

For a number of industrial applications, it is useful to determine sample surface parameters such as thicknesses of thin films and their refractive indices. These parameters may be determined by a number of techniques. Among the better known non-destructive testing techniques are those of spectroreflectometry and spectroscopic ellipsometry.

In spectroreflectometry, an incident radiation beam reflects from a sample, and the intensity of the reflected radiation is analyzed to determine properties of the sample. The incident radiation may include multiple frequency components so that a spectrum of measured data (known as the reflectance spectrum or relative reflectance spectrum) is measured. U.S. Patent No. 5,747,813 describes a type of broadband spectroreflectometer; this patent is incorporated herein in its entirety by reference.

A spectroscopic ellipsometer is described in U.S. Patent No. 5,608,526, which is incorporated herein in its entirety by reference.. As described in this patent, an incident radiation beam having a known polarization state is reflected from a sample, generally at a large angle of incidence and the polarization of the reflected radiation is analyzed to determine properties of the sample. The polarization of the reflected radiation is altered from that of the incident beam so that the change of

polarization state in amplitude and phase is measured to determine the thicknesses and refractive indices of thin films on the surface of the sample.

Spectroreflectometry is simpler and less expensive than spectroscopic ellipsometry, but spectroscopic ellipsometry is more accurate and sensitive to surface properties than spectroreflectometry. While spectroreflectometry and spectroscopic ellipsometry are useful non-destructive testing techniques, it may be difficult to use such techniques to measure certain surface parameters, such as surface birefringence.

It is therefore desirable to provide an improved measurement system for measuring sample parameters such as birefringence. It may also be desirable to provide a polarimeter system for measuring properties of the sample surface to supplement the above-described non-destructive testing techniques.

SUMMARY OF THE INVENTION

The polarimetry system proposed by Applicants retains the simplicity of the spectroreflectometer but is as sensitive to surface properties as the spectroscopic ellipsometer. A polarized sample beam of broadband radiation is focused onto the surface of a sample and the radiation modified by the sample is collected. The sample beam focused to the sample has a multitude of polarization states. The radiation modified by the sample is analyzed with respect to a polarization plane to provide a polarimetric spectrum. Thickness and refractive index information may then be derived from the spectrum. Preferably the polarization of the sample beam is altered only by the focusing and by the sample, and the analyzing is done with respect to a fixed polarization plane.

In the preferred embodiment, the focusing of the sample beam and the collection of the modified radiation are repeated employing two different apertures to detect the presence or absence of a birefringence axis in the sample. In another preferred embodiment, the above-described technique may be combined with ellipsometry for determining the thicknesses and refractive indices of thin films.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view of a combined instrument including a spectroscopic ellipsometer and a polarimetric system to illustrate the preferred embodiment of the invention.

Fig. 2 is a perspective view of the polarimetric system of Fig. 1.

FIG. 3A is a simplified schematic view of a portion of the system of Fig. 1 for measuring polarimetric parameters.

Fig. 3B is a graphical illustration of the illuminating aperture of Fig. 2A.

Fig. 4 is a simplified schematic view of a portion of a system for measuring polarimetric parameters to illustrate an alternative embodiment of the invention.

Fig. 5A is a simplified schematic view of the system for measuring polarimetric parameters of Fig. 1 where the optical path of the illumination beam or the reflected beam is passed through an aperture to illustrate the preferred embodiment of the invention.

Fig. 5B is a schematic view of the aperture of Fig. 5A relative to axes of birefringence of the sample to illustrate the invention.

Fig. 6 is a schematic view of a wheel with four different apertures, with three of the apertures having polarizers therein to illustrate the preferred embodiment of the invention.

For simplicity in description, identical components are identified by the same numerals.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 is a schematic view of a combined instrument including a spectroscopic ellipsometer and a polarimetric system to illustrate the preferred embodiment of the invention. Before the spectroscopic ellipsometer of the combined instrument is discussed, the polarimetric system 8 is first described in some detail in reference to Figs. 1 and 2. As indicated below, while preferably system 8 is advantageously used together with a spectroscopic (or single wavelength)

ellipsometer as in the combined instrument of Fig. 1, this system can also be advantageously used by itself for measuring samples.

The overall optical arrangement in polarimetric system 8 resembles the spectroreflectometer described in U.S. Patent No. 5,747,813 and retains its simplicity. However, different from such spectroreflectometer, system 8 of this invention measures polarimetric reflectance spectrum rather than polarization insensitive reflectance spectrum as in the system of U.S. Patent No. 5,747,813. System 8 is therefore more sensitive to surface properties than the system of U.S. Patent No. 5,747,813. While in the preferred embodiment, the invention is illustrated as detecting radiation reflected by the sample, it will be understood that the invention will function essentially as described herein where radiation transmitted by the sample is detected instead; such and other variations are within the scope of the invention. For simplicity, the preferred embodiment will be described below as measuring the reflected radiation, with the understanding that such description can be readily extended to measure the transmitted radiation.

The convention for showing the sample path, reference path, field illumination path, measurement illumination path and ellipsometer path are shown in the upper right-hand corner of Fig. 1. As noted above, the overall optical arrangement in the system for measuring polarimetric parameters is described below in reference to Figs. 1and 2.

Each of Figs. 1 and 2 shows the same embodiment of an optical system according to the present invention for measuring polarimetric parameters. Part of the focusing and other optical elements of system 8 and the spectroscopic ellipsometer of Fig. 1 are omitted in Fig. 2 to simplify the figure. The elements are explained below in conjunction with the figure which most clearly shows their placement with respect to other elements. Referring to Fig. 1, an optical system 8 for measuring the relative reflectance spectrum of a wafer 3 includes an illumination subsystem, a reflectometer subsystem, a viewing subsystem, and an autofocus subsystem, wherein any given optical element may be part of more than one subsystem. The illumination subsystem includes a lamp 10, such as a xenon

arc lamp, which emits a light beam 12 of visible and/or ultraviolet (UV) light, a lamp housing window 14, an off-axis paraboloidal mirror 16, a flip-in UV cutoff filter 18, a color filter wheel 20, a flat mirror 22, a concave mirror 24, an aperture mirror 28 with a flip-in 40 μm fine focus aperture 30, a large achromat 32, a field illumination shutter 31, a fold mirror 36, and a small achromat 38. In Fig. 2, objective 40 includes mirrors and a housing 40' enclosing mirrors 40a, 40b, but leave sufficient spacing between the housing and the wafer for the oblique illumination beam from the spectroscopic ellipsometer (not shown in Fig. 2).

The illumination system provides a combined beam 42 comprising a measurement beam 25 and a field illumination beam 34. Lamp 10 emits light beam 12 through a lamp housing window 14. The lamp housing window is not necessary for optical reasons; however it is provided to contain lamp 10 should the lamp crack and explode. A xenon lamp is preferred over other lamps such as tungsten or deuterium lamps, because a xenon lamp will give a flatter output covering a spectrum from UV to near infrared. To provide a sample beam having components of wavelengths in a range including 190-220 nm, an additional deuterium lamp 88 is used in combination with the xenon lamp 10 to cover a broader spectrum that includes the deep UV. By using the two lamps together, the resulting combined spectrum of radiation supplied for detecting samples can be extended to a range of about 190 to 800 or 830 nm. Extending the spectrum to the deep UV range is useful for photolithography. Radiation from lamp 88 is focused by lens 93 and reflected by mirror 95 to filter 18 and combined with the radiation from the lamp 10 to form the combined beam 12'. By moving mirror 95 into or out of the path of beam 12 along arrow 99, it is possible to include or exclude radiation from the deuterium lamp 88 from the measurement beam 25.

Off-axis paraboloid mirror 16 collimates light beam 12, which after combination with the radiation from the lamp 88 to form beam 12', can be optionally filtered by flip-in UV cutoff filter 18 and color filter wheel 20. Flip-in UV cutoff filter 18 is used in part to limit the spectrum of light beam 12', so that when light beam 12' is dispersed by a diffraction grating, the first and second order diffraction

beams do not overlap. Part of light beam 12' is reflected by flat mirror 22 onto concave mirror 24 to form measurement beam 25. Concave mirror 24 focuses measurement beam 25 onto the aperture in aperture mirror 28.

Another part of light beam 12, field illumination beam 34, is focused by large achromat 32 near fold mirror 36, causing fold mirror 36 to reflect an image of lamps 10, 88 toward small achromat 38. Small achromat 38 collects the light in field illumination beam 34 before the light reflects off aperture mirror 28. Aperture mirror 28 is a fused silica plate with a reflective coating on one side, with a 150 µm square etched from the reflective coating to provide an aperture for measurement beam 25. The aperture is placed at one conjugate of an objective 40. The field illumination can be turned off by placing field illumination shutter 31 in the optical path of field illumination beam 34.

The narrow measurement beam 25 and wide field illumination beam 34 are rejoined at aperture mirror 28, with field illumination beam 34 reflecting off the front of aperture mirror 28, measurement beam 25 passing through the aperture and polarizer 102, which may be moved into or out of the path of beam 25 by a motor 101.

Fig. 1 shows the reflectometer, viewing and autofocus subsystems of optical system 8, including objective 40, a beam divider mirror 45, a sample beam 46, an optional reference beam 48, a concave mirror 50, a flat mirror 43, a reference plate 52 with a reference spectrometer pinhole 56, a sample plate 54 with a sample spectrometer pinhole 58, a second fold mirror 68, a diffraction grating 70, a sample linear photodiode array 72, a reference linear photodiode array 74, an achromat 80 with a short focal length, mirror 82, a beamsplitter cube 84, a penta prism 86, achromat 90 with long focal lengths, a neutral density filter wheel 97, a third fold mirror 91, and a video camera 96. Some of these components are not shown in Fig. 2, for clarity.

Several magnifications are possible for objective 40. In one embodiment, a Schwarzchild design all-reflective objective may be mounted on a rotatable turret which allows for one of several different objectives (not shown) to be placed in the

optical path of sample beam 46. It is possible to include a refractive element of low power in the optical path of sample beam 46 without significantly affecting the measurements in this invention.

The measurement of the relative reflectance spectra of wafer 3 will now be described. When field illumination shutter 31 is placed in the path of field illumination beam 34, combined beam 42 comprises only measurement beam 25. Combined beam 42 is split by beam divider mirror 45, a totally reflecting mirror placed so as to deflect half of combined beam 42 towards objective 40, thus forming sample beam 46, the undeflected half of combined beam 42 forming reference beam 48. Because sample beam 46 and optional reference beam 48 are derived from the same source, lamps 10 and 88, and because combined beam 42 is radially uniform, reference beam 48 and sample beam 46 have proportionally dependent spectral intensities. Furthermore, since beam divider mirror 45 is a totally reflecting mirror in half of an optical path rather than a partially reflecting mirror in the entire optical path, a continuous broadband spectrum is reflected with good brightness.

Reference beam 48 does not initially interact with beam divider mirror 45, but instead illuminates concave mirror 50. Concave mirror 50 is slightly off-axis, so that reference beam 48 is reflected onto the reverse face of beam divider mirror 45, where flat mirror 43 re-reflects reference beam 48 into alignment with reference spectrometer pinhole 56. Flat mirror 43 is provided to realign reference beam 48 with sample beam 46 so that both beams pass through their respective spectrometer pinholes substantially parallel. This allows for simpler alignment of the spectrometer element for both channels, since the reference beam enters the spectrometer parallel to the sample beam.

Since reference beam 48 does not interact with the surface of beam divider mirror 45 which reflects beam 46, there is no loss in reference intensity as reference beam 48 passed beam divider mirror 45. While reference beam 48 does interact with a mirror 43 on the reverse side of beam divider mirror 45, these two mirrors are independent, since no light passed through beam divider mirror 45.

Indeed, in an alternative embodiment where the two reflecting surfaces of beam divider mirror 45 cannot easily be placed together on one optical element, the reflecting surfaces exist on separate mirror elements.

The focal length of concave mirror 50 is such that reference beam 48 is in focus at reference spectrometer pinhole 56. The light passing through reference spectrometer pinhole 56 and reflecting off fold mirror 68 is dispersed by diffraction grating 70. The resulting first order diffraction beam is collected by reference linear photodiode array 74, thereby measuring a relative reference spectrum.

Polarized sample beam 46 is reflected off beam divider mirror 45 towards objective 40, where sample beam 46 is focused onto wafer 3, and the reflected sample beam 46' is focused by objective 40 onto sample spectrometer pinhole 58. The reflected sample beam 46' does not interact with beam divider mirror 45 on the reflected path, because reflected sample beam 46' passed through the space behind beam divider mirror 45, where reference beam 48 also passes. The radiation from reflected sample beam 46' from the sample 3 passes through an analyzer 104 before it reaches pinhole 58. The light passing through sample spectrometer pinhole 58 and reflecting off fold mirror 68 is dispersed by diffraction grating 70 according to wavelength of the light. As with the reference beam, the resulting first order diffraction beam of the sample beam is collected by sample linear photodiode array 72, thereby measuring the sample polarimetric spectrum. Because the two beams cross at diffraction grating 70, the photodiode array apparently aligned with sample beam 46 in Fig. 2 is in fact the photodiode array for reference beam 48, and vice versa. The polarizer 102 and analyzer 104 do not rotate and are preferably stationary. Analyzer 104 therefore analyzes the radiation modified by the sample and collected by objective 40 according to a fixed plane of polarization.

The relative reflectance spectrum can then be simply obtained by dividing the sample light intensity at each wavelength by the relative reference intensity at each wavelength. Typically, this might involve 512 division computations, where 512-diode linear photodiode arrays are used to record the sample and reference

spectra. In the preferred embodiment, the spectrum ranges from about 190 nm to 800 or 830 nm.

In one embodiment of the present invention, diffraction grating 70 is a concave holographic grating and the spectrometer pinholes are 15 mm apart. The diffraction grating is holographically corrected to image multiple spectra, since the 15 mm spacing does not allow for both beams to be centered on the grating. One such grating is a multiple spectra imaging grating supplied by Instruments S.A. Also, the grating is designed so that the angle of the detector causes reflections off the detector to fall away from the grating.

Combined beam 42, which may include field illumination, is reflected off beam divider mirror 45 toward wafer 3. When reflectance spectra measurements and autofocusing are being performed, the field illumination is off to minimize scattered light.

Because of the innovative arrangement of optical elements used to measure relative reflectance spectra, many of the elements of in the spectra measurement subsystem are also used in the autofocus subsystem. For example, since relative reflectance spectrum measurement in the embodiment shown in the figures uses beam divider mirror 45 as opposed to a partially reflecting mirror, the resulting beam reflected from the wafer 3 has a circularly asymmetric cross section. This allows for detecting the direction of focus as well as the relative distance to move objective 40 or wafer 3 to achieve an in-focus condition, whereas with a circularly symmetric cross section, the direction of focus cannot be detected.

The polarimetric system 8 in Figs. 1 and 2 differs from that described in U.S. Patent No. 5,747,813 in that the sample beam 46 is polarized in the system of this application. Thus, when the sample beam 46 is reflected by objective 40 towards the sample 3, the beam that is focused onto the wafer has a multitude or a plurality of different polarization states. This is illustrated more clearly in reference to Figs. 3A, 3B. Sample beam 46 is reflected by mirror 40a towards mirror 40b which then focuses the beam towards the sample 3 as shown in Fig. 3A. Fig. 3B is a schematic view of the illumination aperture of the sample beam 46 when focused onto the

wafer 3. The various quantities in Figs. 3A, 3B are defined by reference to cylindrical coordinates ρ, ϕ and θ, where ρ is the radius of a point (distance to the origin) in the coordinate system, ϕ the angle of a plane normal to the sample surface containing the point to a reference plane normal to the surface of the sample, and θ the angle from the normal to the sample surface of a line connecting the point to the origin (angle of incidence to the normal).

In reference to Fig. 3A, it is assumed that polarizer 102 has a plane of polarization defined by the plane at ϕ_p, so that the sample beam 46 that emerges from the polarizer and reflected by beam divider 45 also has this polarization. When beam 46 is reflected first by mirror 40a and then by mirror 40b which focuses the beam onto the sample 3, the beam that is focused onto the sample 3 arrive in different planes of incidence as illustrated in Figs. 3A, 3B. In Fig. 3B, the plane of polarization ϕ_p of the beam 46 is indicated at 103.

From the description above, beam divider mirror 45 deflects about half of the polarized beam to become the sample beam 46 and passes the remaining half of the beam as the reference beam 48. For this reason, the illumination aperture (shaded area 106) in Fig. 3B appears to be approximately semicircular in shape. Thus the radiation that is focused onto sample 3 by objective 40 will be incident onto the sample at planes of incident that span the semicircular area. The radiation incident on the wafer in one plane of incidence at one value of the angle ϕ in the area will have s- and p-polarizations that are different from those of radiation in a different plane of incidence having a different value of the angle ϕ in the area. The s- and p-polarizations of radiation in different planes of incidence will, by definition, have different orientations, so that the polarization state of the incident radiation in one plane of incidence will be different from that of the incident radiation in a different plane of incidence. Therefore, the radiation incident upon sample 3 will have a multitude or plurality of polarization states as a function of ϕ.

The beam that is focused onto sample 3 will be reduced in intensity compared to sample beam 46 as a function of the combined reflection coefficients of the objectives 40a, 40b as explained below. The radiation originating from sample

beam 46 and focused onto the sample by objective 40 is reflected by the sample which again reduces the intensity and changes the phase of each polarization component as a function of the reflection coefficients of the sample. Such radiation is again reflected by objective 40 through a beam divider 45 and analyzer 104 to the spectrometer as described above. While in the preferred embodiment, the same objective used for focusing the radiation onto the sample is also used for collecting the reflected radiation towards the analyzer and spectrometer; it will be understood that this is not required, and a different collection objective may be used in addition to the focusing objective; such and other variations are within the scope of the invention.

Consider the radiation incident from point 105 with coordinates (ρ, ϕ) of Fig. 3A in the semicircular illumination aperture with the polarization along the ϕ_p direction towards the origin on the sample surface. The electric field can be decomposed in the s- and p-polarizations shown in Figs. 3A, 3B as follows:

$$\vec{E}_{in} = E_0\hat{p}_p = E_s^{in}\hat{\phi} + E_p^{in}(-\hat{\rho})$$

$$E^{in} = E_s^{in}\hat{p}_p \cdot \hat{\phi} = E_0\sin(\phi_p - \phi)$$

$$E_p^{in} = E_0\hat{p}_p \cdot (-\hat{\rho}) = -E_0\cos(\phi_p - \phi)$$

where E_{in} is the electric field of the radiation in beam 46 after being polarized by the polarizer 102, E_0 its amplitude, and E_s^{in}, E_p^{in} the components of the radiation along the s- and p-polarizations. After the radiation exits the objective,

$$\vec{E}_{out} = E_s^{out}\hat{\phi} + E_p^{out}(-\hat{\rho})$$

$$E_s^{out} = E_0 r_s^o r_s^s \sin(\phi_p - \phi)$$

$$E_p^{out} = - E_0 r_p^o r_p^s \cos(\phi_p - \phi)$$

where E_{out} is the electric field of the radiation in beam 46 after being reflected by the sample 3, and E_s^{out}, E_p^{out} its components along the s- and p-polarizations; and where $r_s^s(r_s^o)$ and $r_p^s(r_p^o)$ are the reflection coefficients for the s- and p-polarizations for the sample (objective). The reflection coefficients for the objective are the product of the reflection coefficients of the two mirrors as shown in Fig. 3A, i.e., $r_s^o = r_s^{o1} r_s^{o2}$ and $r_p^o = r_p^{o1} r_p^{o2}$. The electric field at the spectrometer after passing through the analyzer with polarization plane at ϕ_a will be along $\hat{p}_a$ can be obtained:

$$\vec{E}_{spectrometer} = E_0 r_s^o r_s^s \sin(\phi_p - \phi)\sin(\phi_a - \phi)\left[1 + \frac{r_p^o r_p^s}{r_s^o r_s^s}\cot(\phi_p - \phi)\cot(\phi_a - \phi)\right]\hat{p}_a$$

The detector current can be expressed as

$$I_{det} \propto \int_0^{\phi_o}\int_0^{\rho_o} \rho \, d\rho \, d\phi \, |E_{spectrometer}|^2 \qquad (1)$$

If the polarizer 102 is omitted, then the detector current for semicircular apertures becomes

$$I_{\det} \propto \frac{1}{2}|E_0|^2\left[R_s^O R_s^S + R_p^O R_p^S\right] \qquad (2)$$

In equation (2), $R_s^O, R_s^S, R_p^O, R_p^S$ are defined respectively as $|r_s^O|^2, |r_s^S|^2, |r_p^O|^2, |r_p^S|^2$. One must keep in mind that r_s^O, r_s^S, r_p^O *and* r_p^S are functions of the angle of incidence, i.e., functions of ρ. Where polarizer 102 is in place as shown in Figs. 1-3, a general equation can be derived where the intensity at the spectrometer is a function of the s- and p-reflectivities of the sample and of the objectives and of Δ^o, Δ^s which are defined by the equations $r_p^O / r_s^O = \tan\psi^o e^{j\Delta^o}$, $r_p^S / r_s^S = \tan\psi^s e^{j\Delta^s}$ (where r_p^S, r_s^S are the complex reflection coefficients of the sample surface of radiation at p- and s-polarizations and where r_p^O, r_s^O are the complex reflection coefficients of the objectives of radiation at p- and s-polarizations), where ψ^o, ψ^s, Δ^o and Δ^s are also the ellipsometric parameters. Therefore, system 8 is polarization sensitive.

Shown below are some special cases:

(3)

A. $\phi_0 = \pi$

$$I_{det} \propto \int_0^{\rho_o} \rho d\rho |E_0|^2 \left[R_s^O R_s^S\left(\frac{\pi}{4} + \frac{\pi}{8}\cos(2\phi_p - 2\phi_a)\right) + R_p^O R_p^S\left(\frac{\pi}{4} + \frac{\pi}{8}\cos(2\phi_p - 2\phi_a)\right) + \frac{\pi}{4}\cos(2\phi_p - 2\phi_a)\sqrt{R_s^O R_s^S R_p^O R_p^S}\cos(\Delta^o + \Delta^s)\right]$$

For the system to be sensitive to the change in Δ, $2(\phi_p - \phi_a) = m\pi$. If $\phi_p = \phi_a$,

(4)

$$I_{\text{det}} \propto \frac{\pi}{8} \int_{0}^{\rho_o} \rho d\rho \, |E_0|^2 \left[3R_s^O R_s^S + 3R_p^O R_p^S + 2\sqrt{R_s^O R_s^S R_p^O R_p^S} \cos(\Delta^o + \Delta^s) \right]$$

(5)

B. $\phi_0 = \pi/2$

$$I_{\text{det}} \propto \frac{\pi}{8} \int_{o}^{\rho_o} \rho d\rho |E_o|^2 \left[\begin{array}{l} R_s^O R_s^s \left(\frac{\pi}{4} + \frac{\pi}{8}\cos(2\phi_p - 2\phi_a) - \frac{1}{4}\sin(2\phi_p) - \frac{1}{4}\sin(2\phi_p) \right) \\ + R_p^O R_p^s \left(\frac{\pi}{4} + \frac{\pi}{8}\cos(2\phi_p - 2\phi_a) + \frac{1}{4}\sin(2\phi_p) + \frac{1}{4}\sin(2\phi_p) \right) + \frac{\pi}{8}\cos(2\phi_p - 2\phi_a)\sqrt{R_s^O R_s^s R_p^O R_p^s}\cos(\Delta^o + \Delta^s) \end{array} \right]$$

(6)

If $\phi_p = \phi_a = \pi/2$,

$$I_{\text{det}} \propto \frac{\pi}{8} \int_{0}^{\rho_o} \rho d\rho |E_0|^2 \left[R_s^O R_s^S \left(\frac{3\pi}{8} - \frac{1}{2} \right) + R_p^O R_p^S \left(\frac{3\pi}{8} + \frac{1}{2} \right) + \frac{\pi}{8} \sqrt{R_s^O R_s^S R_p^O R_p^S} \cos(\Delta^o + \Delta^s) \right]$$

From the above analysis, the $\cos(\Delta^o + \Delta^s)$ coefficients in the third term in equations (4) and (6) are the largest when the polarizer and analyzer angles are the same, that is, when the polarizer 102 and the analyzer 104 have substantially the same plane of polarization. In other words, we can use a single polarizer to act both as the polarizer and analyzer as shown in Fig. 4. As shown in Fig. 4, the polarizer 116 may be used to replace the polarizer 102 and analyzer 104. The sample channel of the photodiode array will be proportional to equation (5). In this configuration, only one polarizer is needed, and the polarizer and analyzer are self-aligned. As yet another alternative, the polarizer 102 and analyzer 104 may be omitted altogether

if the divider 45 is a polarizing beam splitter. For improved sensitivity of film thickness detection, a waveplate or other retarder element 190 shown in dotted line may be inserted between the beam divider 45 and analyzer 104 in Fig. 1, to introduce a phase shift in the argument of cosine coefficients $\cos(\Delta^{o} + \Delta^{s})$ in the third term in equations (4) and (6). Preferably, the phase shift in the collected radiation caused by the element 190 prior to analyzing and dispersion is about $\pi/4$. The thickness of the mirror coating of the mirrors 40a, 40b may also be selected to enhance sensitivity in detection of thicknesses of thin films so that the total change in phase in the radiation focused and collected by the mirrors 40a, 40b is about $\pi/2$. This will then cause Δ^{o} to be $\pi/2$ in the argument of cosine coefficients $\cos(\Delta^{o} + \Delta^{s})$ in the third term in equations (4) and (6), so that the cosine term in these equations converts to a sine term.

The polarimetric spectrum measured in terms of the detector currents in array 72 may be used for deriving useful information about the sample 3. For example, if the types of materials in a number of different layers on sample 3 are known so that one can estimate their refractive indices, such detector currents may be adequate for deriving the thicknesses and accurate refractive indices of the layers. Methods for such derivation is known to those skilled in the art and need not be discussed in detail here. Alternatively, the detector signals may be combined with ellipsometry measurements for deriving film thicknesses and refractive indices. Using broadband radiation for detection in the polarimetric system is advantageous, since one can obtain data points at a number of different wavelengths. Such wealth of data points is very useful for determining the thicknesses and refractive indices of multiple layers on the sample, and may permit one to apply more accurate curve fitting algorithms or to cross-check the accuracy of the measurements.

The system 8 can also be used to analyze in-plane birefringence samples through two measurements, each with one of the two quadrants of the illumination aperture covered. As shown in Fig. 3B, the illumination aperture is substantially semicircular and contains the first and fourth quadrants 106a, 106b. Figs. 5A, 5B show illumination only through the first quadrant (shaded area), and the reflection

of the illumination beam passes through only the third quadrant 106d. When the first quadrant is covered and the fourth quadrant not covered, a second measurement is then performed with the illumination through the fourth quadrant, and reflection through the second quadrant is collected and measured in a similar manner. This is effectively the same as physically rotating the wafer 3 by 90 degree. Because the axes of birefringence line up differently with the planes of incidence for first and fourth quadrant illumination, the birefringence effects can be deduced from the two successive measurements. If the locations of axes of birefringence with respect to the wafer are known, the measurement can be optimized by orienting the locations of the four quadrants so that the first and the fourth quadrants 106a, 106b are centered about corresponding axes of birefringence, such as about the ordinary and extraordinary axes respectively. As shown in Fig. 5B, where the fourth quadrant of the polarizer 102 is covered and it is assumed that the polarization axis 103 of the polarizer 102 is aligned with the axis of birefringence of the wafer, the first quadrant 106a is centered about an axis of birefringence. A first polarimetric spectrum is obtained. The polarizer 102 may then be rotated 90° by a rotating means (not shown) so that the fourth quadrant 106b is now assumed to be centered about the axis of polarization and the first quadrant is covered instead, and a second polarimetric spectrum is obtained. A comparison of the first and second spectra will indicate the presence of any axis or axes of birefringence in the wafer 3. Even where the first and fourth quadrants are not centered about the axis of the polarizer, a comparison of the two spectra may still reveal axis or axes of birefringence.

The above-described method for detecting birefringence of crystals may also be performed using a rotatable wheel 200 shown in FIG. 6. Thus, the polarizer 102 of FIG. 1 may be replaced by wheel 200. In order to perform the measurement described above in reference to FIG. 1 to detect polarimetric parameters, wheel 200 is rotated until the polarizer 201 at position 1 is in the path of the illumination beam passing through the aperture 28 to the beam divider 45. The illumination aperture will consist of the first and fourth quadrants 106a, 106b, and the reflection from the wafer 3 will be collected through an aperture in the second and third quadrants.

Where it is desirable to block or cover the first quadrant 106a in Figs. 4B, 6B, wheel 200 is rotated until polarizer 202 in position 2 is in the path of the radiation beam between aperture mirror 28 and beam divider 45. The illumination aperture will consist only of the fourth quadrant 106b, and the reflection from the wafer 3 will be collected only through aperture 106c in the second quadrant. Where it is desirable to block or cover the fourth quadrant 106b instead, wheel 200 is rotated until the polarizer 203 in position 3 is in the optical path. The illumination aperture will consist only of the first quadrant 106a, and the reflection from the wafer 3 will be collected only through aperture 106d in the third quadrant. Where it is desirable to operate in the same manner as U.S. Patent 5,747,813, wheel 200 is rotated until an aperture 204 in position 4 with no polarizer therein is in the optical path of the beam between aperture mirror 28 and beam divider 45.

While in the embodiments described above, birefringence detection is achieved by using different illumination apertures, essentially the same result can be achieved by using collection apertures instead. In other words, instead of blocking part of the illumination aperture in the path of the illumination radiation beam, part of the collection aperture in the path of radiation reflected from the sample and then collected and directed to the spectrometer and detector may be blocked or covered instead. Such and other variations are within the scope of the invention.

The application using system 8 for detecting birefringence is described above. System 8 can also be used for detecting other parameters of the sample surface. From the equations and the description above in reference to the Figures, especially FIGS. 3A and 3B, the reflected spectrum detected by spectrometer of photodiode array 72 use information concerning Δ, a polarimetric parameter commonly used in ellipsometry and related to thicknesses and refractive indices of thin films at the surface of the sample. Therefore, if certain aspects of the sample surface are known, such known aspects may be combined with the information concerning polarimetric parameters measured by system 8 to derive useful information on the sample, such as film thicknesses and refractive indices.

In the preferred embodiments, the reflected spectrum obtained from photodiode array 72 is compared to the reference spectrum from photodiode array 74 to derive polarimetric parameters, thereby improving signal to noise ratio. For some applications, however, such polarimetric parameters may be derived from the reflected spectrum alone, without the use of a reference spectrum. For such applications, the reference beam 48 is not required, so that all the components associated with the generation of beam 48 and the reference spectrum may be omitted in Figs. 1 and 2. Such and other variations are within the scope of the invention.

The spectroscopic ellipsometer 300 in the combined instrument of FIG. 1 will now be described. As shown in FIG. 1, a portion of the radiation originating from the xenon arc lamp 10 that has passed through focus 18 and 20 is diverted by a beam splitter 302 to a fiber optic cable 304 which supplies the radiation to a collimator 306. After being collimated, the beam is polarized by polarizer 310 and is focused by focus mirror 312 to the wafer 3. The reflection of such beam is collected by a collection mirror 314 and reflected by folding mirror 316 through an analyzer 320 before it is supplied to spectrometer 322 and detector 324 for detection. The polarizer 310 and analyzer 320 are rotated relative to each other so that the amplitude and phase of the change in polarization state of the beam 308 caused by the reflection at the wafer 3 can be measured. For a more detailed description of the operation of the spectroscopic ellipsometer 300, please see U.S. Patent 5,608,526.

To measure a sample with layers of thin film, it may be desirable to employ a combined instrument, including system 8 for measuring polarimetric parameters and spectroscopic ellipsometer 300, as shown in FIG. 1. System 8 and spectroscopic ellipsometer 300 are arranged so that sample beam 46 and sample beam 308 are focused onto substantially the same spot on the wafer 3. The polarimetric parameters measured by system 8 may then be combined with the ellipsometric parameters measured by system 300 for deriving useful information such as film thicknesses and film refractive indices. The polarimetric parameters obtained by system 8 and the ellipsometric parameters obtained using system 300

may be combined using techniques such as that described in "ANALYSIS OF SEMICONDUCTOR SURFACES WITH VERY THIN NATIVE OXIDE LAYERS BY COMBINED IMMERSION AND MULTIPLE ANGLE OF INCIDENCE ELLIPSOMETRY", Ivan OHLIDAL and Frantisek LUKES, Applied Surface Science 35 (1988-89) 259-273, North Holland, Amsterdam.

Even though the spectral range of spectroscopic ellipsometers does not extend to the deep UV such as about 193 nm, by using the combined instrument, it is possible to accurately measure the indices of refraction at such wavelength. Thus, the combined instrument may be used for measuring the indices of refraction over the combined spectra of the spectroscopic ellipsometer and the polarimeter system 8. By using the combined instrument, and data from both system 8 and from the spectroscopic ellipsometer, the thicknesses and refractive indices of different films of the sample at wavelengths in the spectrum of the spectroscopic ellipsometer can be found. This thickness information may be used together with data from the combined instrument to find the refractive indices of the films in the deep ultraviolet region. The numbers of detectors in the arrays 72, 74 and detector 324 in spectrometer 322 may be chosen to obtain data at the desired wavelengths for optimum results.

In an alternative embodiment, sample beams 46 and 308 need not be focused on the same spot on wafer 3. Wafer 3 may be moved by rotation or linear translation, or a combination of the two motions, in a conventional manner so that spots measured by system 8 are subsequently measured by system 300, or vice versa, and so that data obtained by the two systems measuring the same spot may be combined in the same manner as that described above. Since the rotational and translational of motions are controlled, the relative locations of the spots being measured by the two systems 8 and 300 can be correlated.

While preferably a spectroscopic ellipsometer is combined together with the polarimetric system 8 as described, it is also possible to combine system 8 with a single wavelength ellipsometer. For this purpose, the arrangement in Fig. 1 needs to be modified only slightly by removing the diffractive grating in the optical path of

the spectrometer 322, between mirror 321 and detector 324. A laser with wavelength in the polarimetric spectrum may be used as the radiation source for the single wavelength ellipsometer. With the measurements taken by means of the single wavelength ellipsometer and by means of system 8, it is still possible to derive film thicknesses and indices of refraction at wavelengths over the polarimetric spectrum.

While the invention has been described above by reference to various embodiments, it will be understood that changes and modifications may be made without departing from the scope of the invention, which is to be defined only by the appended claims and their equivalents.